

Higgs Searches at LEP

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The four LEP experiments ALEPH, DELPHI, L3 and OPAL have performed decay-mode independent searches for scalar bosons, flavour-independent Higgs boson searches, searches for Higgs bosons in the Standard Model and several Two-Higgs-Doublet models and searches for doubly charged Higgs bosons at centre-of-mass energies up to 209 GeV. The results obtained and mostly combined by the LEP Higgs working group are discussed.

1 Introduction

During the last years of running of the e^+e^- collider LEP, searches for Higgs bosons and hence for the origin of electroweak symmetry breaking have been of highest interest. The search for the MSSM and in particular for the Standard Model (SM) Higgs bosons have been pursued by the four LEP experiments and the results have been combined by the LEP Higgs Working Group for optimal search sensitivity. This article describes the present status of the search for Higgs bosons at LEP, mostly results as combined by the LEP Higgs working group, or analyses prepared for future combination by single experiments.

Most Higgs searches at LEP were limited in their sensitivity by the provided centre-of-mass energy. Hence they profited significantly from the outstanding performance of the LEP machine experts, who managed to push the centre-of-mass energies to extreme values, allowing the experiments each to record about 700 pb^{-1} of data above $\sqrt{s} \approx 160 \text{ GeV}$, 450 pb^{-1} of which above 192 GeV and up to 209 GeV.

The data included in the analyses presented here have been subject to at least one additional turn of calibration after data taking. In particular the jet energy scales and the precision

tracking and b-tagging are highly sensitive to this and therefore reached in most cases almost final precision.

The different Higgs boson searches in this presentation are ordered in terms of increasing model dependence, starting from a fully decay-mode independent search for scalar bosons, the search for purely hadronically decaying Higgs bosons (‘flavour-independent search’) and the Standard Model Higgs boson followed by various searches in different types of 2-Higgs Doublet Models and their interpretations, in particular in the MSSM model, and ending with the search for doubly charged Higgs bosons.

2 Decay-Mode Independent Higgs Search

These analyses¹ represent topological searches for new neutral scalar bosons S^0 with a minimum number of model assumptions. The new bosons are only assumed to be produced in association with a Z^0 boson via the Bjorken process $e^+e^- \rightarrow S^0 Z^0$, where S^0 denotes, depending on the context, any new scalar neutral boson. The analyses are based on studies of the recoil mass spectrum of $Z^0 \rightarrow e^+e^-$ and $\mu^+\mu^-$ events and on a search for $S^0 Z^0$ events with $S^0 \rightarrow e^+e^-$ or photons and $Z^0 \rightarrow \nu\bar{\nu}$. They are sensitive to all decays of the S^0 into an arbitrary combination of hadrons, leptons, photons and invisible particles, and to the case of a long-lived S^0 leaving the detector without interacting. The analyses are applied to the full LEP 1 Z^0 resonance data (115.4 pb⁻¹ at $\sqrt{s} = 91.2$ GeV) and the 662.4 pb⁻¹ of LEP 2 data collected at centre-of-mass energies in the range of 183 to 209 GeV.

The results (figure 1) are presented in terms of limits on the scaling factor k , which relates the $S^0 Z^0$ production cross-section to the SM cross-section for the Higgs-Strahlung process via:

$$\sigma_{S^0 Z^0} = k \cdot \sigma_{H_{SM}^0} (m_{H_{SM}^0} = m_{S^0}) \quad (1)$$

where it is assumed that k does not depend on the centre-of-mass energy for any given m_{S^0} .

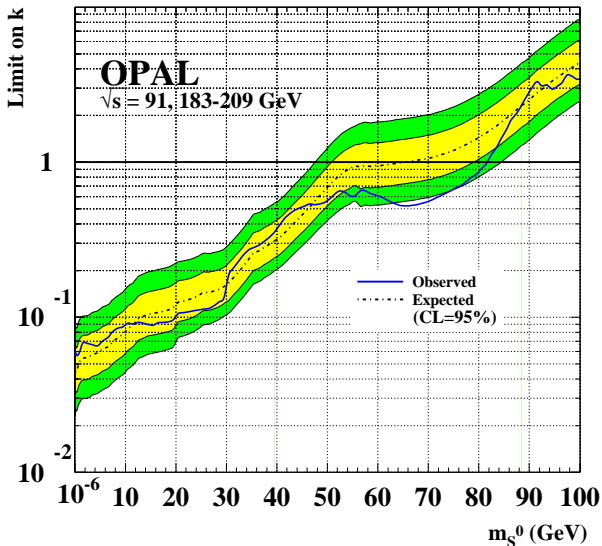


Figure 1: Exclusion limit for the scale factor k on the cross-section for the production of a new scalar boson in the Higgs-Strahlung process (solid line), together with the expected median for background-only experiments (dot-dashed) and the 68% and 95% probability intervals shown as light and dark shaded bands.

Values for $k \geq 0.1$ are excluded for m_{S^0} below 19 GeV, whereas $k = 1$, i.e. the SM rate for Higgs boson production, is excluded for m_{S^0} up to 81 GeV, independent of the decay modes of the S^0 boson. For masses well below the width of the Z^0 , i.e. $m_{S^0} \leq 1$ GeV, the obtained limits remain constant at the level of $k_{obs.}^{95} = 0.067$, and $k_{exp.}^{95} = 0.051$.

These results are also used to investigate and interpret two scenarios with continuous mass distribution, due to one single broad state (‘stealthy Higgs scenario’) or several states close in mass (‘uniform Higgs scenario’)¹. The results will also be included in future model interpretations and combinations by the LEP Higgs working group.

3 Flavour-Independent Higgs Search

There are extensions of the Standard Model in which Higgs bosons have suppressed couplings to b-quarks. This can occur for specific parameters of the Two Higgs Doublet Model, or of the Minimal SuperSymmetric Model, as well as for some composite models. Standard Model searches would have a reduced sensitivity in such cases, because of their strong reliance on the identification of the b-quark from the Higgs boson decay to maximize the separation power. It is important to cover such scenarios experimentally with dedicated searches in which the information from the flavour of the quarks in the Higgs boson decay is not exploited, so that the model dependence of the final Higgs search result can be reduced.

All four LEP collaborations have pursued such *flavour-independent* searches in the recent years, analysing the four-jet ($q\bar{q}q\bar{q}$), missing energy ($q\bar{q}\nu\bar{\nu}$) and leptonic ($q\bar{q}l^+l^-$) topologies. None has found evidence for a signal. The LEP Higgs Working Group has combined the search results for the $e^+e^- \rightarrow Z^{0*} \rightarrow hZ^0$ production mechanism². They are presented in terms of upper limits on the corresponding cross-section as a function of the Higgs bosons mass, and of a lower limit on the mass, assuming a production cross-sections equal to those in the Standard Model and the Higgs boson decaying to 100% into hadrons. Higgs mass assumptions from 60 to 115 GeV were tested. The analyses have been mostly developed based on the corresponding Standard Model analyses, but removing the *b*-tag and using test-mass dependent selections.

The combined observed and median expected limits are 112.9 and 113.0 GeV/c², respectively. The confidence level for the background-only hypothesis fluctuates around 0.5 as expected for the background. The sensitivity for a 5-sigma discovery is reached for a 107 GeV/c² Higgs boson.

These results have been and will be used in further model interpretations, in particular for models with reduced Higgs coupling to b-quarks.

4 Standard Model Higgs Search

The Standard Model predicts one single neutral scalar Higgs boson. Its mass is arbitrary, but confined between about 130 and 190 GeV from self-consistency of the model. Indirect experimental constraints from precision measurements of electroweak parameters yield a preferred Higgs boson mass of $m_H = 88_{-33}^{+53}$ GeV, and the 95% confidence level upper bound on the mass is 196 GeV³.

At LEP energies, the SM Higgs boson is expected to be produced mainly in association with a *Z* boson through the Higgs-Strahlung process $e^+e^- \rightarrow HZ$. For masses in the vicinity of 115 GeV (the kinematic limit for Higgs-Strahlung at $E_{CM} \approx 206$ GeV), the SM Higgs boson is expected to decay mainly into $b\bar{b}$ quark pairs (74%) while decays to tau lepton pairs, WW^* , gluon pairs ($\approx 7\%$ each), and $c\bar{c}$ ($\approx 4\%$) are all less important. The final-state topologies are determined by these decays and by the decay of the associated *Z* boson. The searches at LEP encompass the four-jet final state ($H \rightarrow b\bar{b}q\bar{q}$), the missing energy final state ($H \rightarrow b\bar{b}\nu\bar{\nu}$), the leptonic final state ($H \rightarrow b\bar{b}l^+l^-$ where *l* denotes an electron or muon, and the tau lepton final states ($H \rightarrow b\bar{b}\tau^+\tau^-$ and ($H \rightarrow \tau^+\tau^-)(Z \rightarrow q\bar{q})$).

The four LEP experiments perform their analyses in these search channels using combinations of preselections and likelihood or neural network techniques. The statistical analysis and combination of the data is done using the likelihood ratio $-2\ln Q$ as test-statistic. Details on the analyses and the statistical combination method can be found in⁴ and references therein.

Figure 2 shows the test-statistic $-2\ln Q$ as a function of the test-mass for the combination of LEP data. The expected curves and their spreads are obtained by replacing the observed data configuration by a large number of simulated event configurations. The observed minimum in $-2\ln Q$ at $m_H = 115.6$ GeV indicates a deviation from the background hypothesis. The

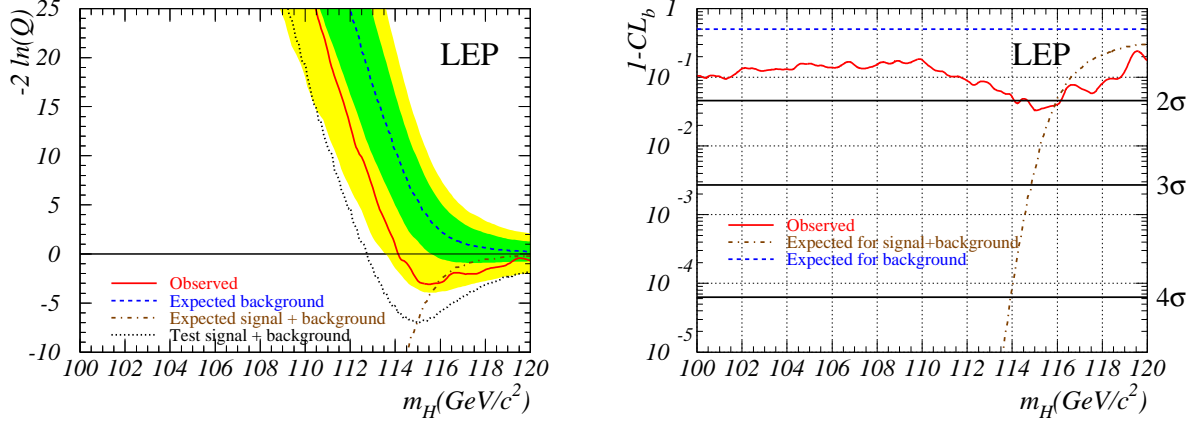


Figure 2: Left: Observed (solid line) and expected (dashed-dotted line) behaviour of the likelihood ratio $-2 \ln Q$ as a function of the test-mass m_H . Dark/light shaded bands around the median expected line correspond to the $\pm 1/\pm 2$ standard deviation spreads; dotted line: result of a test where 115 GeV Higgs boson signal is added to background. Right: The probability $1 - CL_b$ as a function of the test-mass m_H . Solid line: observation; dashed/dashed-dotted lines: expected probability for the background/signal+background hypotheses.

persistent tail in the observation towards lower test-masses where the observed curve stays below the prediction for the background has been reproduced in a simulation where a 115 GeV Higgs boson signal was injected in the background simulation and propagated through the likelihood ratio calculation. Studies on contributions from individual experiments and final-state topologies have shown that the signal-like behaviour in the vicinity of $m_H = 115$ GeV mainly originates from the ALEPH data and is concentrated in the four-jet channel. The DELPHI data and the combined missing energy channel are rather background like.

Figure 2 shows the confidence level $1 - CL_b$, which is a measure of the compatibility of the observation with the background hypothesis and calculated from $-2 \ln Q$, as a function of the test-mass hypothesis. At $m_H = 115.6$ GeV, where the likelihood ratio has its minimum, $1 - CL_b = 0.034$, which corresponds to about a two standard deviation excess in the LEP data.

The confidence level $CL_s = CL_{s+b}/CL_b$, which is a measure of the compatibility with the signal+background hypothesis, is used to set mass exclusion limits. The test-mass corresponding to $CL_s = 5\%$ defines the lower bound at the 95% confidence level. The expected and observed lower bounds obtained for the SM Higgs boson mass are 115.4 GeV and 114.1 GeV, respectively, at 95% confidence level.

These results include the final L3 data⁵ and preliminary data from ALEPH, DELPHI and OPAL. In the meantime ALEPH has published their final analysis⁶. The final publication by DELPHI and OPAL are imminent and will be followed by a last and final combination of the LEP Higgs Working Group, expected for the summer 2002.

5 Two-Higgs Doublet Model Higgs Searches

5.1 Introduction

Beyond the Standard Model, with only one physical neutral Higgs scalar, it is important to study extended models containing more than one physical Higgs boson. In particular, Two Higgs Doublet Models (2HDM) are attractive extensions of the SM since they add new phenomena with the fewest new parameters: they satisfy the constraints of $\rho \approx 1$ and the absence of tree-level flavour changing neutral currents, if the Higgs-fermion couplings are appropriately chosen. In the context of 2HDMs the Higgs sector comprises five physics Higgs bosons: two neutral CP-even scalars, h^0 and H^0 (with $m_h < m_H$), one CP-odd scalar, A^0 , and two charged

scalars, H^\pm . At the centre-of-mass energies accessed by LEP, the h^0 and A^0 bosons are expected to be produced predominantly via two processes: the Higgs-Strahlung process $e^+e^- \rightarrow h^0 Z^0$ and the associated-production $e^+e^- \rightarrow h^0 A^0$. The cross-sections for these two processes are related at tree level to the SM cross-section by the following relations:

$$e^+e^- \rightarrow h^0 Z^0 : \quad \sigma_{hZ} = \sin^2(\beta - \alpha) \sigma_{HZ}^{SM} \quad (2)$$

$$e^+e^- \rightarrow h^0 A^0 : \quad \sigma_{hA} = \cos^2(\beta - \alpha) \bar{\lambda} \sigma_{HZ}^{SM} \quad (3)$$

where $\tan \beta = v_2/v_1$ is the ratio of the the vacuum expectation values, α is the mixing angle between h and H and $\bar{\lambda}$ is a kinematic term.

In the 2HDM (type II) the first Higgs doublet (Φ_1) couples only to down-type fermions and the second Higgs doublet (Φ_2) couples only to up-type fermions. In the type I model, quarks and leptons do not couple to the first Higgs doublet, but couple to the second Higgs doublet.

5.2 2HDM Parameter Scan

Using all available channels with and without b-tagging requirements and adding in constraints from the invisible Z width as measured by LEP, Γ_Z , a general 2HDM parameter scan has been performed in the range $1 \leq m_h \leq 120$ GeV, $3 \text{ GeV} \leq m_A \leq 2 \text{ TeV}$, $0.4 \leq \tan \beta \leq 58.0$ and for $\alpha = \pi/2, \pi/4, 0, -\pi/4, -\pi/2$.

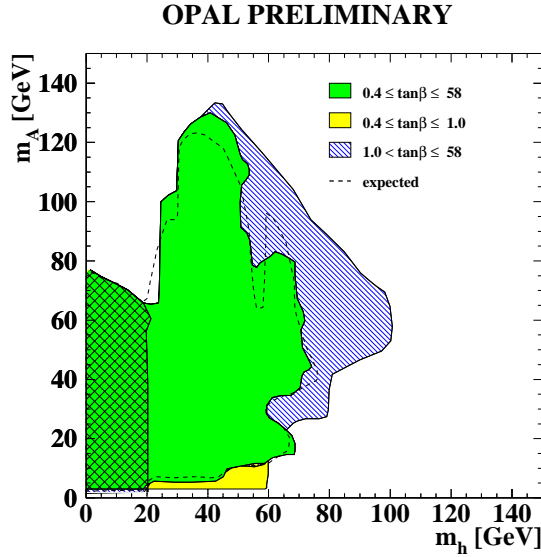


Figure 3: Excluded (m_A, m_h) region independent of α , together with the expected exclusion limit. A particular (m_A, m_h) point is excluded at 95% CL if it is excluded for $0.4 \leq \tan \beta \leq 58.0$ (dark grey region), $0.4 \leq \tan \beta \leq 1.0$ (lighter grey region) and $1.0 \leq \tan \beta \leq 58.0$ (hatched region) for $-\pi/2 \leq \alpha \leq \pi/2$. The cross-hatched region is excluded using the constraints from Γ_Z only. Expected exclusion limits are shown as a dashed line.

The exclusion limits are presented in several projections of the parameters involved, where a point is excluded at 95% confidence level if it is excluded for all parameters scanned over. An example for such a projection of excluded parameter regions is shown in figure 3. Further details of the scan and its results can be found in⁷. A combination of all available LEP data in such a general 2HDM (type II) interpretation is planned for the near future.

5.3 MSSM Higgs Searches

The Higgs boson sector of the MSSM corresponds to a 2HDM(type-II) model. This implies that the decay branching ratios of the Higgs bosons to fermions depend not only on the masses, but also on the values of α and β while the production cross-sections are related to the SM ones as detailed in equation 2 and 3. For this analysis, the searches for the $e^+e^- \rightarrow h^0 Z^0$ processes which are used in the Standard Model interpretations, are combined with the searches for the

$e^+e^- \rightarrow h^0 A^0$ process. The $b\bar{b}$ and $\tau^+\tau^-$ decays of the h^0 and A^0 are dominant for such models, and the searches concentrate on these decays only. In addition, for models in which the decay branching ratios of the Higgs to $b\bar{b}$ and $\tau^+\tau^-$ are suppressed, the flavour-independent results of section 3 are also used. The $h^0 Z^0$ and $h^0 A^0$ searches at LEP shown here use a combination of all LEP Higgs searches conducted at centre-of-mass energies between ~ 88 GeV and 209 GeV.

The presence of an MSSM Higgs boson is tested using three benchmark scenarios. (a) The *no-mixing* scenario assumes no mixing between the left- and the right-handed stop quarks, where the following parameters are chose: $M_{SUSY} = 1$ TeV/ c^2 , $M_2 = 200$ GeV/ c^2 , $\mu = -200$ GeV/ c^2 , $X_t (= A - \mu \cot \beta) = 0$, $0.4 < \tan \beta < 50$ and 4 GeV/ $c^2 < m_A < 1$ TeV/ c^2 with $m_{top} = 175$ GeV/ c^2 . (b) The m_h -*max* scenario is designed to yield the maximal value of m_h in the model. It therefore corresponds to the most conservative range of $\tan \beta$ -values for fixed values of the mass of the top quark and M_{SUSY} . The choice of parameters is identical to the one in (a) except that $X_t = 2 M_{SUSY}$. (c) The *large- μ* scenario with parameters $M_{SUSY} = 400$ GeV/ c^2 , $\mu = 1$ TeV/ c^2 , $M_2 = 400$ GeV/ c^2 , $m_{\tilde{g}} = 200$ GeV/ c^2 , $4 \leq m_A \leq 400$ GeV/ c^2 , $X_t = -300$ GeV/ c^2 , is designed to illustrate choices of MSSM parameters for which the Higgs boson h does not decay into $b\bar{b}$ due to large corrections from SUSY loop processes. While kinematically fully accessible, this scenario requires the flavour-independent search.

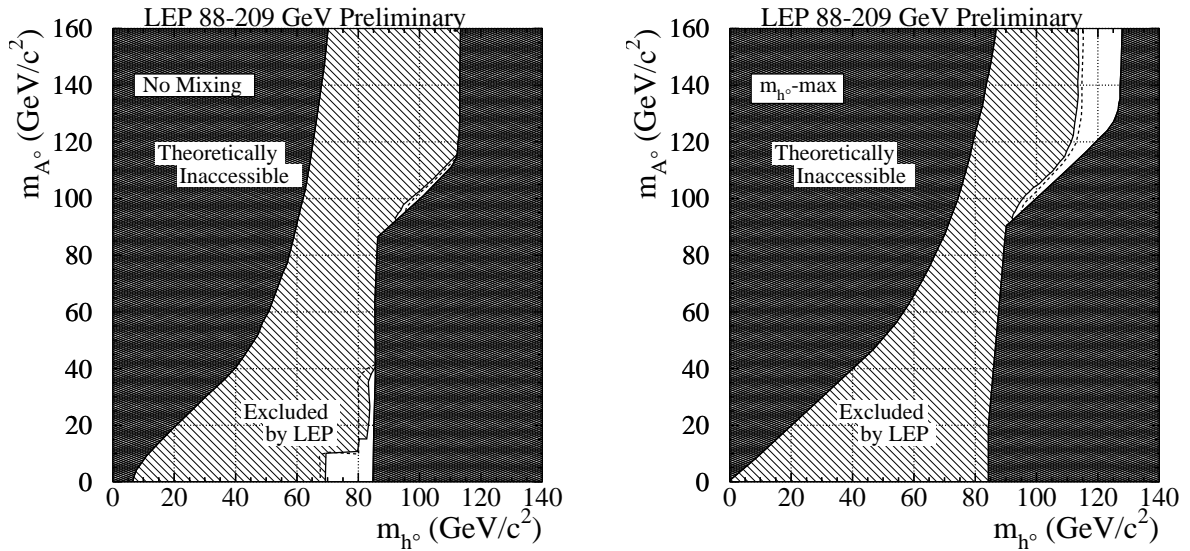


Figure 4: The MSSM exclusion for the no-mixing benchmark scenario (left) and the m_h -max scenario (right). The figures show the excluded and the theoretically disallowed regions as a function of the Higgs boson masses.

Studying the m_h -*max* scenario, a few small excesses of events are seen in single channels or single experiments at $(m_h, m_A) \sim (83, 83)$ GeV/ c^2 , near $(m_h, m_a) \sim (93, 93)$ GeV/ c^2 , at $m_h \approx 97$ GeV/ c^2 and at about $m_h \approx 115$ GeV. The latter is due to the events which already caused the excess in the SM Higgs search. The significance of these excesses is always close to 2σ and can, in the case close to the mass diagonal, be excluded by the combination of channels and experiments. Figure 4 shows the excluded region for scenario (a) and (b) in the Higgs mass plane. The *no-mixing* scenario is almost completely excluded and further constraints in the low m_A region can be imposed using the searches for the charged Higgs bosons. The m_h -*max* scenario shows unexcluded region at large m_h and large $\tan \beta$. The corresponding limits in Higgs masses and $\tan \beta$ are given in table 1.

Adding in the flavour-independent analyses provides enough sensitivity to exclude the entire *large- μ* scenario at 95% confidence level, also the previously unexcluded parameter points. Further details on the data, the analyses and the model interpretations can be found in ⁸.

Scenario	m_h limit (GeV/c ²) obs. (exp.)	m_A limit (GeV/c ²) obs. (exp.)	Excluded $\tan \beta$ observed limit (expected limit)
m_h -max	91.0 (94.6)	91.9 (95.0)	$0.5 < \tan \beta < 2.4$ ($0.5 < \tan \beta < 2.6$)
no-mixing	91.5 (95.0)	92.2 (95.3)	$0.7 < \tan \beta < 10.5$ ($0.8 < \tan \beta < 16.0$)

Table 1: Limits on m_h and m_A in the m_h -max and no-mixing benchmark scenarios for $m_{top} = 174.3$ GeV. The median expected limits in an ensemble of SM background-only experiments are listed in parentheses.

5.4 Charged Higgs Searches

2HDM models also predict charged Higgs bosons. At LEP2 energies charged Higgs bosons are expected to be produced mainly through the process $e^+e^- \rightarrow H^+H^-$. 2HDMs do not predict the H^\pm mass, and the tree-level cross-section is fully determined by the mass. The searches are carried out under the assumption that the two decays $H^+ \rightarrow c\bar{s}$ and $H^+ \rightarrow \tau^+\nu$ exhaust the H^+ decay width, but the relative branching ratio is free.

The four LEP experiments use for this search in total 2500 pb⁻¹, 510 pb⁻¹ of which above 206 GeV centre-of-mass energy. As described in⁹, the search channels are: $(c\bar{s})(\bar{c}s)$, $(\tau^+\nu)(\tau^-\bar{\nu})$ and the mixed mode $(c\bar{s})(\tau^-\bar{\nu}) + (\bar{c}s)(\tau^+\nu)$.

Taking the lowest observed limit for any branching ratios, the charged Higgs boson can be excluded up to $m_{H^\pm} = 78.6$ GeV/c² while the corresponding expected limit is 78.8 GeV/c² at 95% CL. The observed upper limit on the charged Higgs cross-section as a function of the charged Higgs boson mass is found to be always within the 1 σ band around the expected median, except a small range around $m_{H^\pm} \approx 67$ GeV/c² reaching about 2 σ , caused by an excess of events in one experiment (L3). This effect is under investigation.

In the 2HDM (type I) the bosonic decay $H^\pm \rightarrow W^{\pm*}A^0$ dominates near $\tan \beta > 1$, if kinematically allowed. Recently a new analysis¹⁰, searching for $H^+H^- \rightarrow W^*AW^*A \rightarrow q\bar{q}b\bar{b}q\bar{q}b\bar{b}$, $H^+H^- \rightarrow W^*AW^*A \rightarrow \nu b\bar{b}q\bar{q}b\bar{b}$, $H^+H^- \rightarrow \tau\nu W^*A\tau\nu q\bar{q}b\bar{b}$ has been performed. The exclusion limits range from $m_{H^\pm} > 60$ GeV/c² to $m_{H^\pm} > 80$ GeV/c² and from $m_A > 10$ GeV/c² to $m_A > 72$ GeV/c², depending on $\tan \beta$ and (m_{H^\pm}, m_A) . As soon as more than one experiment has carried out such an analysis the results may be combined by the LEP Higgs Working Group.

5.5 Fermiophobic Higgs Searches

In 2HDM (type I) and other models, the Higgs coupling to fermions can be small and the Higgs bosons therefore decay preferentially to pairs of bosons. These are the so-called ‘‘fermiophobic’’ Higgs bosons. Inspired by several fermiophobic models, a benchmark fermiophobic model is defined, with Standard Model production rates and channels, but with the fermionic channels closed. Since the photonic Higgs decays dominate in this scenario below $m_H \approx 90$ GeV, the LEP experiments performed searches for hZ production with subsequent $h \rightarrow \gamma\gamma$ decays¹¹.

The combination of the LEP data results in an upper limit on the branching ratio $B(h \rightarrow \gamma\gamma)$ as a function of the Higgs bosons mass m_h . For the fermiophobic benchmark a lower Higgs mass limit of $m_h > 108.2$ GeV/c² with an expected median limit of $m_h > 109.0$ GeV/c² is obtained.

DELPHI and L3 have turned their photonic Higgs searches also into limits on anomalous couplings on $H \rightarrow \gamma\gamma$, $H \rightarrow \gamma Z$ and $H \rightarrow ZZ$ ¹² which might be combined in the future.

5.6 Search for Light Yukawa Production

Within a 2HDM a search for the Yukawa process $e^+e^- \rightarrow b\bar{b}A/h \rightarrow b\bar{b}\tau^+\tau^-$ in the mass range of 4-12 GeV has been performed, using the data collected by the OPAL¹³. Within a CP-conserving 2HDM(type II) the cross-section for Yukawa production depends on $\xi_d^A = |\tan \beta|$ and $\xi_d^h = |\sin \alpha / \cos \beta|$ for the production of the CP-odd A and the CP-even h , respectively.

From the data 95% CL upper limits are derived for ξ_d^A within the range of 8.5 to 13.6 and for ξ_d^h between 8.2 to 13.7, depending on the mass of the Higgs boson, assuming a branching ratio fraction into $\tau^+\tau^-$ of 100%. An interpretation of the limits within a 2HDM (type II) with Standard Model particle content is also given.

6 Search for Doubly Charged Higgs Bosons

Doubly charged Higgs bosons ($H^{\pm\pm}$) appear in theories beyond the Standard Model, for example in left-right symmetric models. Such models in which $SU(2)_R$ gauge symmetry is broken by triplet Higgs fields do not conserve baryon and lepton numbers. Searches for pair-produced doubly charged Higgs bosons have recently been performed by DELPHI and OPAL¹⁴ using the data collected at centre-of-mass energies between 189 and 209 GeV. At the 95% CL, lower limits for the mass of doubly charged Higgs bosons in left-right symmetric models have been set at 99.1 GeV/c² and 98.5 GeV/c² by DELPHI and OPAL, respectively. These results might be combined by the LEP Higgs working group in the future.

7 Conclusion

The four LEP experiments have searched for Higgs bosons in several models with varying model dependence. Most of the results have been combined by the LEP Higgs Working Group resulting in various exclusion limits on Higgs boson masses, production cross-sections or decay branching ratios. In the search for the Standard Model Higgs, a $\approx 2\sigma$ excess has been observed at a mass of $m_h = 115.6$ GeV/c². First final combinations by the LEP Higgs Working Group are planned for the summer 2002.

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